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THE NASA QUIET ENGINE

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ABSTRACT

The NASA Quiet Engine Program will incorporate all available noise reduction technology into a propulsion system suitable for subsonic civil transport aircraft. Full-scale experimental hardware is being built and tested primarily for noise performance. The program is in process and component tests to date indicate that it is possible to achieve or exceed noise reduction objectives of 15-20 perceived noise decibels below the levels of 707/DC-8 long-range transport aircraft.

INTRODUCTION

In response to mounting public concern over the noise pollution caused by civil jet aircraft, the National Aeronautics and Space Administration initiated the Quiet Engine Program in 1966. The objective of the program was to incorporate the available noise reduction technology into a propulsion system for subsonic civil transport aircraft. The specific goal chosen was noise levels 15-20 perceived noise decibels below the noise levels of the long range Boeing 707 and McDonnell-Douglas DC-8 transports under comparable operating conditions. These noise reductions were to be achieved on a complete propulsion system. Thus, proper engine design characteristics and an acoustically treated nacelle would be used to effect this noise signature improvement. The three main technological advances which would make such a gain possible are: 1) development of the high-bypass-ratio engine with its low jet noise signature, 2) improved understanding of the fan noise generation process and 3) development of nacelle acoustic lining technology. The application of these developments to a complete propulsion system was thought to be an adequate basis for attainment of the previously stated noise goals of 15-20 PNdB below 707/DC-8 levels.

QUIET PROPULSION SYSTEM DESIGN STUDIES

The general outline of the Quiet Engine Program was thus established. However, implementation of this program in experimental hardware required many detailed design decisions. The major characteristics of the Quiet Engine were determined by in-house and industry design studies carried out under NASA contracts. Pratt and Whitney Division of United Aircraft Corporation and Allison Division of General Motors conducted the contract studies. The results are reported in

(1)* and (2). Cycle characteristics were explored in detail, mechanical arrangements were screened, single and two-stage fans were considered, engine weights were estimated, and engine noise characteristics were predicted. Since engine technology is advanced to the point where a wide range of engine choices is available, an optimum system could be selected primarily on the basis of noise considerations.

The principal noise sources considered in the engine selection were the fan machinery noise and the fan and core jet noise. The fan machinery noise is generated by the interaction of the rotating and stationary blade rows of the fan with the air flow through these cascades. The generation process is not completely understood, but the noise is generated in close proximity to the blades and is propagated out the inlet and exhaust ducts of the nacelle. The noise from this source spans a wide range of frequencies and thus is said to be broad-band. A typical fan noise spectrum is shown in figure 1. A large fraction of the radiated sound power is, however, present in a fundamental blade passing frequency and its harmonics. The fundamental occurs in the range of a few thousand cycles per second for fans designed with currently available aerodynamic and mechanical design techniques. For supersonic tip speed operation of the fan, low frequency discrete tones appear in the spectrum at integral multiples of the shaft rotational frequency. A general discussion of fan noise is presented in (3).

Because human annoyance response varies markedly as a function of acoustic frequency, an annoyance weighting factor has been developed. The resultant noise units are perceived noise decibels. Figure 2 presents the variation of fan machinery noise in PNdB as a function of fan pressure ratio for a fixed

*Numbers in parentheses designate References at end of paper.

thrust level of 90,000 pounds, approximately that required for an airplane such as the DC-8/707. For fan pressure ratios above about 1.8, a two-stage fan is required which available acoustic data indicate to be noisier than a single-stage fan by 5-10 PNdB. As pressure ratio decreases, fan size, and hence the size of the noise source, increases. However, the intensity of the noise source decreases as the pressure ratio decreases because the tip speed of the fan decreases. Noise source intensity appears to correlate most strongly with the fan tip speed. The resultant variation is as shown in figure 2 with a decrease in fan noise as fan pressure ratio is decreased.

Nacelle acoustic lining can decrease the noise experienced by a far-field observer. The amount of reduction that is practical has not been defined by adequate system studies. The McDonnell-Douglas Company has performed a detailed analysis of the integration of a Quiet Engine with the DC-8 airframe (4). Their design included acoustic lining to achieve a 10 PNdB suppression of the fan noise. A sketch of the installation is shown in figure 3. The general conclusion was that the use of the Quiet Engine with its current technology high bypass cycle was feasible and resulted in an improvement in the DC-8 performance. Subsequent tests at NASA Lewis Research Center indicated that noise reductions of the order of 15 PNdB could be achieved on the high-bypass fan just as Boeing and McDonnell-Douglas had shown could be achieved on the low bypass JT3D engine. The fan noise spectrum of figure 1 is reduced by the use of acoustic lining as shown in figure 4. The values shown on figure 5 are based on a 15 PNdB fan noise reduction by the use of nacelle acoustic lining.

The other important components of the engine noise signature are generated by the fan jet and core jet mixing with the surrounding atmosphere. The principal correlating parameter for the jet mixing noise is the jet velocity.

Recent work reported in (5) indicates that the correlation is with jet velocity to the eighth power even in the low velocity regime (below 1000 feet per second). By use of the correlations of (5), the jet mixing noise was estimated as a function of fan pressure ratio for typical engines. These estimates are shown on figure 6. The suppressed fan machinery noise and jet mixing are reasonably well balanced in the neighborhood of a fan pressure ratio of 1.5. The corresponding engine bypass ratio is in the 5-8 range, depending on the characteristics of the core gas generator. From considerations such as these, a set of engine specifications was developed for a low-noise engine suitable for long-range conventional take-off and landing (CTOL) aircraft.

More detail on the engine design studies is presented in (1) and (2) and also summarized in (6), (7), and (8). These design studies elucidated several points.

1. The suppressed fan noise was the component of the engine noise with the greatest uncertainty.

2. The estimated noise performance of the Quiet Engine propulsion system indicated that the program objectives of a 15-20 PNdB noise reduction could be realized. A set of engine specifications was developed to guide the detailed design and fabrication of an experimental Quiet Engine.

3. The use of Quiet Engines on a DC-8 airframe would produce a superior aircraft. However, the lower fuel consumption of the aircraft with Quiet Engines would not be adequate by itself to justify economically the retrofitting of the DC-8 fleet.

The response to the first conclusion was the development of an outdoor fan acoustic test facility capable of testing fans of full size (72-inch diameter) for the Quiet Engine. The facility and some of the early experimental results are discussed in (9), (10), and (11). The facility has been modified to produce better noise measurements and now appears as in the photograph of figure 7 and the plot plan of figure 8. Several fans designed for pressure ratios between 1.4 and 1.5 have been tested in the facility. Their acoustic performance agrees with the overall estimates of figure 2.

The second point above led to the start of a contract program to build and ground test several models of the Quiet Engine.

THE EXPERIMENTAL QUIET ENGINE

The engine design specifications developed in the design study phase are shown in Table I. A competitive request for proposal was issued in October 1968 for the design, fabrication, and ground test of experimental engines built to these design specifications. The extent of the test program was defined as 250 hours of engine testing on 10 builds of the experimental engine hardware. In July 1969 a fixed-price contract for approximately $20 million was awarded to the Aircraft Engine Group of the General Electric Company. This contract provided for the aerodynamic and acoustic evaluation of three fans in full scale, a series of exploratory acoustic tests on one-half scale models of two of these fans, a series of tests on ten engine configurations, and delivery of a test engine with spare parts to Lewis Research Center. At Lewis, the Quiet Engine will be mated to an acoustically treated nacelle to form a low-noise propulsion system - the objective of the Quiet Engine Program.

The design characteristics of the three fans called A, B, and C are listed in Table II. Fans A and B are relatively low-speed units with high aerodynamic loadings to achieve the design 1.5 pressure ratio. Fan C on the other hand is a high-speed unit with moderate aerodynamic loading to achieve its 1.6 design pressure ratio. The two low-speed fans are driven by a moderately loaded four-stage turbine while fan C is driven by a heavily-loaded two-stage turbine. The gas generator used in the engine is that used in the TF-39 and CF-6 engines. For this application it has excess capacity and is not a flight-weight vehicle. However, it duplicates the thermodynamic and aerodynamic parameters identified as desirable in the engine design studies. The use of this developed production core permits a substantial cost saving, decreases program risk, and does not compromise acoustic evaluation. A cutaway view of the vehicle with a low-speed fan is shown in figure 9. Acoustic linings are incorporated in the engine frames between the fan rotor and stator assembly and some distance upstream and downstream of the fan. Acoustic treatment lines the inlet duct to the core engine and the exhaust passage downstream of the fan turbine.

The schedule of these activities is displayed in the bar chart of figure 10. The design of the Quiet Engine was approved by NASA in December 1969. This design is reported in detail in (12). General Electric then proceeded to carry out the fabrication and test phase of the program. As of July 1, 1971, the program status is as follows:

1. Aerodynamic evaluation of fans A, B, and C is complete.

2. Acoustic evaluation of fans A and B is complete.

3. Tests of fan casing boundary-layer suction and serrated leading edges on the half-scale B fan are complete.

4. Tests of the half-scale C fan are underway.

5. Tests of the first engine with the A fan will commence in the summer 1971.

The aerodynamic performance of the three fans will be reported in NASA Contractor reports. The overall performance characteristics of the three fans are summarized in Table III. Comparison with the design predictions of (12) shows that all three fans failed to meet their areodynamic efficiency performance objectives in the hub region. The flow from this section of the fan is fed into the core engine (hot gas generator). In the bypass portion, fans B and C meet and fan A exceeds objective efficiency. Over 80 percent of the flow is through the bypass duct in this high-bypass-ratio engine. Cruise specific fuel consumption is very sensitive to fan bypass efficiency and relatively insensitive to fan core flow efficiency. Thus the overall areo-performance of the fans is quite satisfactory, particularly in view of the limited amount of aerodynamic development provided for in the program.

Fans A and B have been evaluated acoustically at the Lewis Research Center. The overall performance of the fans was generally as anticipated, based on the design predictions and the noise performance correlation discussed earlier. A complete report on the noise performance of these fans exceeds the scope of this paper. Those performance results will be reported in detail in forthcoming NASA publications. The results of the half-scale test program will appear in NASA Contractor reports. Noise spectra with and without nacelle suppression for fans A and B are shown in figure 11. The maximum perceived noise levels for the fans are shown in Table IV. The data were taken with acoustic linings installed in the fan frame extending from in front of the fan to aft of the fan stator as shown in figure 9. For the nacelle suppression data additional acoustic treatment was added in the form of three circular splitter rings and outer duct wall linings in front of the fan and one splitter ring and duct wall linings in the fan exhaust duct. The test data measured on a 100-foot radius are extrapolated to equivalent flyover noise levels for conditions of take-off and approach. The measuring locations are those of the Federal Aviation Regulation Part 36, (13). For take-off, the observer is directly under the flight path at 3.5 nautical miles from brake release; for approach the observer is 1.0 nautical mile from threshold. For these conditions a DC-8 equipped with Quiet Engines is at an altitude of approximately 1000 feet as it passes over the take-off observer. For these data, the engine was assumed to be at full power (no cutback) during take-off with the fan operating at 90 percent of its design speed. At approach the airplane is at 375 feet altitude and the fan is at 60 percent of its design speed. The fan data do not, of course, contain any core engine noise or fan turbine noise. That information can only be obtained from complete engine testing. Equivalent values for the DC-8 with its current engine are in the range of 115 to 120 PNdB. The Quiet Engine fans with nacelle acoustic treatment are about 20 PNdB below the production DC-8 levels.

The regulation controlling the noise levels of new aircraft, (13), is stated in terms of effective perceived noise levels, EPNdB, a noise measuring unit which accounts for the duration of exposure to high noise levels and the presence of discrete frequencies in the noise spectrum. Table V displays the fan noise data in terms of EPNdB. The FAA regulation will permit a new aircraft of the DC-8 size (325,000 pounds gross weight) to produce no more than 104 EPNdB at the take-off location and no more than 106 EPNdB at approach. The levels generated by the fan alone of the Quiet Engine are approximately at these levels without any nacelle acoustic suppression. The use of nacelle acoustic treatment permits the achievement of noise levels about 10 EPNdB below the current FAA regulation levels.

It should be recognized that nacelle acoustic treatment of the design used to achieve these noise results has the potential to penalize aircraft performance. Some of the obvious factors are added drag losses, nacelle weight, and anti-icing requirements. Also the effects of the splitter rings on the aerodynamic performance of the fan or the engine have not been established. These factors will be investigated and assessed in terms of aircraft performance as the engine nacelle design is developed in the program.

CONCLUDING REMARKS

Application of available noise control technology to an aircraft propulsion system should result in systems with noise substantially below current regulation levels. This expectation is based on full-scale fan tests with an acoustically treated nacelle and the best available estimate of other engine noise sources. Engine noise tests will begin in the third quarter of 1971. The Quiet Engine will be installed in an acoustically treated nacelle for test at the NASA Lewis Research Center.

ACKNOWLEDGMENT

The author in making this progress report speaks not only for his associates at the NASA Lewis Research Center but also for those in industry who contribute to the achievements discussed here.

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Table I. - Quiet Engine Design Characteristics

Engine:	
Bypass ratio	5 to 6
Cruise thrust, lb	4900
Take-off thrust, lb	22 000
Fan:	
Number of stages	1
Inlet guide vanes	None
Spacing between rotor and stators	2 rotor chords
Tip speed -	
Take-off, ft/sec	1000
Pressure ratio, cruise	1.5 to 1.6
Compressor:	
Rotors	1 or 2
Maximum pressure ratio per rotor	12.5

Table II. - Quiet Engine Fans Design Characteristics

Design Parameter	Fan A	Fan B	Fan C
Corrected rotor tip speed, ft/sec	1160	1160	1550
Inlet hub/tip radius rotor	0.465	0.465	0.360
Rotor inlet tip diameter, inches	73.354	73.354	68.300
Corrected airflow, lb/sec	950	950	915
Inlet corrected specific flow, lb/sec-sq/ft annulus area	41.3	41.3	41.3
Number of rotor chords axially separating rotor and outer OGV	2.0	2.0	2.0
Number of rotor chords axially separating rotor and inner OGV	1.25	1.25	1.25
Bypass portion total pressure ratio	1.50	1.50	1.60
Hub portion total pressure ratio	1.32	1.43	1.49
Bypass ratio: Design	5.6	5.4	5.0
Rotor aspect ratio	2.32	1.71	2.09
Rotor solidity: OD	1.45	1.30	1.40
ID	2.50	2.16	2.45
Objective bypass adiabatic efficiency	0.865	0.870	0.842
Number of rotor blades	40	26	26
Number of outer OGV's	90	60	60
Number of inner OGV's	90	60	60

Table III - Quiet Engine Fan Aerodynamic Performance

	Fan A	Fan B	Fan C
Air Flow at Design, lbs/sec	977	983	915
Pressure Ratio at Design	1.480	1.484	1.625
Bypass Efficiency at Design	.882	.865	.845
Core Efficiency at Design	.830	.771	.820
Stall Margin at Design Speed	17 °/o	23 °/o	22 °/o

Table IV - Quiet Engine Noise Levels Based on LeRC

Full-Scale Fan Noise Tests

	PERCEIVED NOISE LEVEL, PNdB			
	APPROACH 375-FT ALTITUDE		TAKEOFF 1000-FT ALTITUDE	
	A	B	A	B
4 FANS	104	104	104	104
4 FANS WITH NACELLE SUPPRESSION	96	99	98	100

CORE ENGINE NOISE NOT INCLUDED

Table V - Quiet Engine Noise Levels Based on LeRC

Full-Scale Fan Noise Tests

	NOISE, EPNdB			
	APPROACH 375-FT ALTITUDE		TAKEOFF 1000-FT ALTITUDE	
	A	B	A	B
4 FANS	99	101	105	104
4 FANS WITH NACELLE SUPPRESSION	91	93	95	96

CORE ENGINE NOISE NOT INCLUDED.

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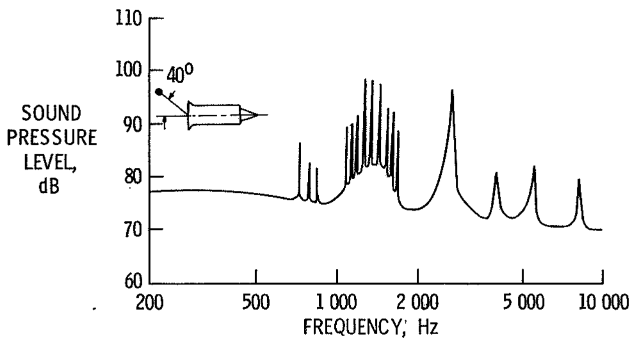

Figure 1. - Fan noise spectrum.

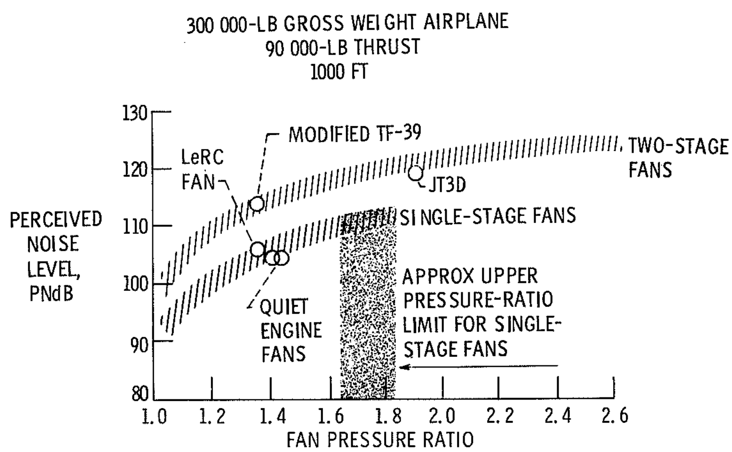

Figure 2. - Fan machinery noise estimates.

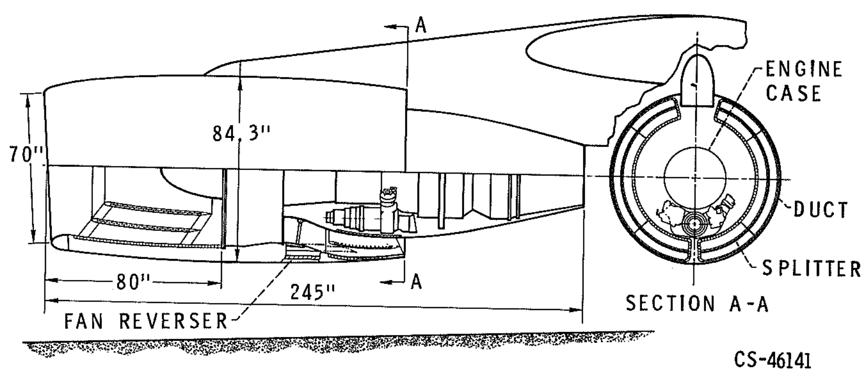

Figure 3. - DC-8 quiet engine nacelle.

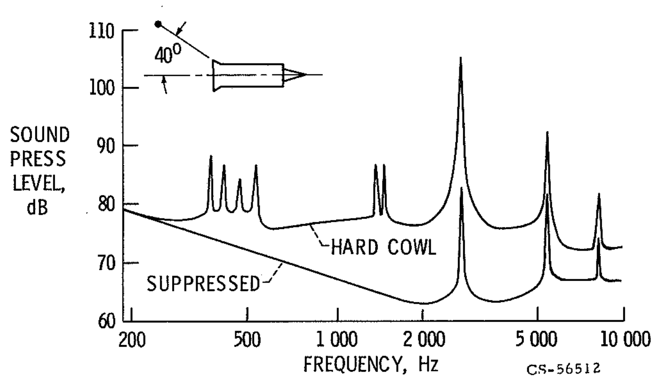

Figure 4. - Fan noise spectra, with and without suppression.

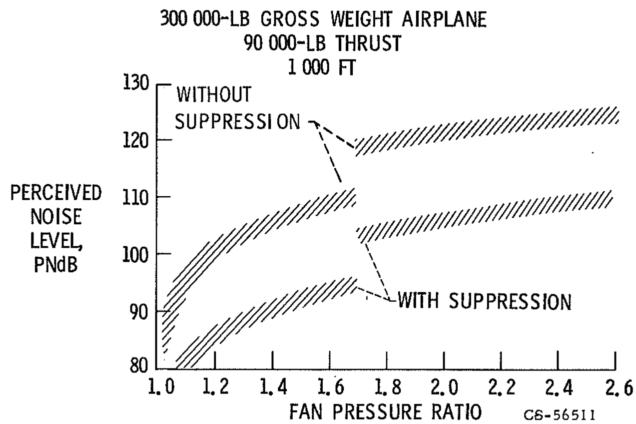

Figure 5. - Fan machinery noise estimates, with and without suppression.

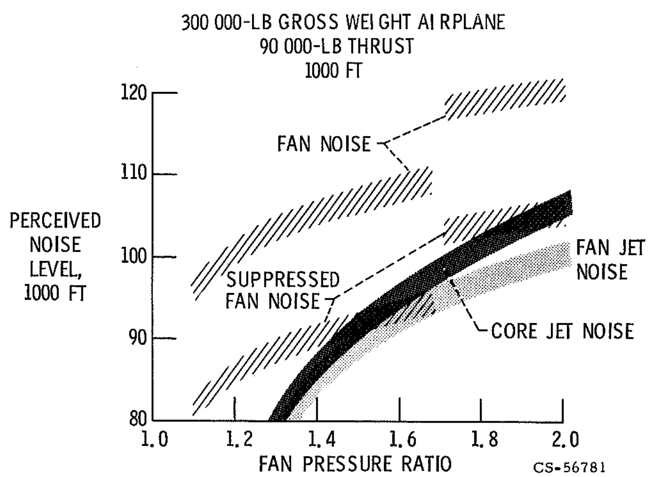

Figure 6. - CTOL propulsion noise estimates.

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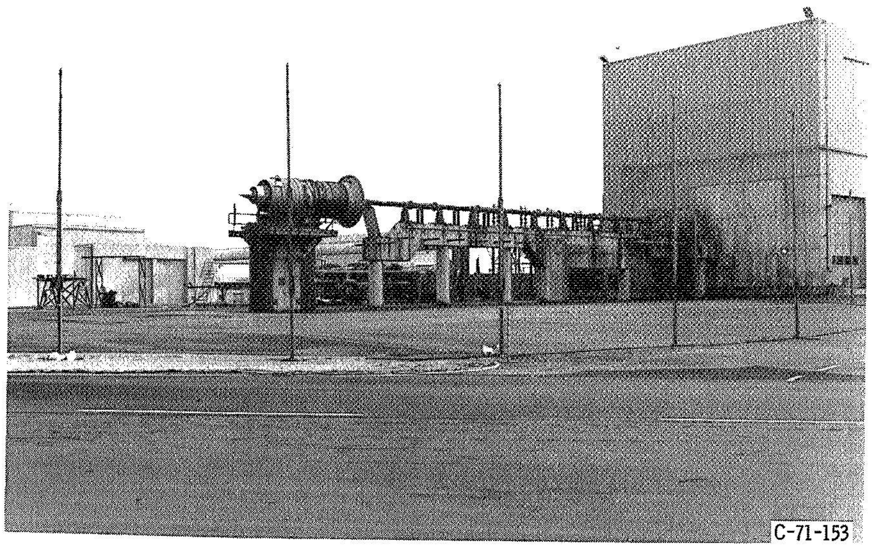

Figure 7. - Full-scale fan acoustic test facility.

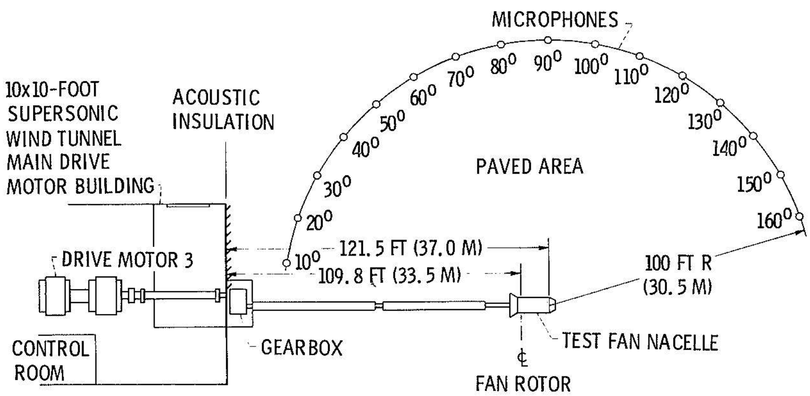

Figure 8. - Plan view of full-scale fan acoustic test facility.

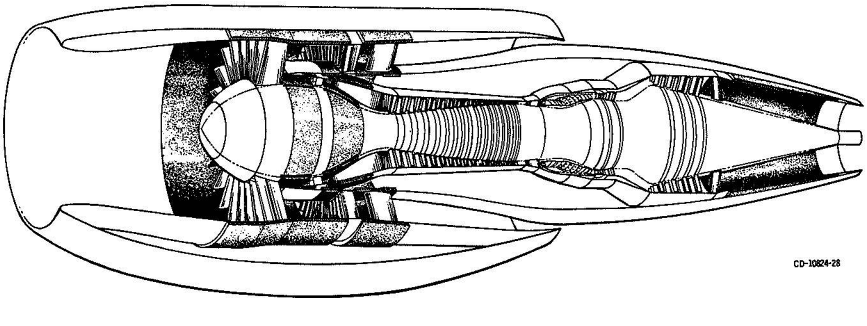

Figure 9. - Experimental quiet engine.

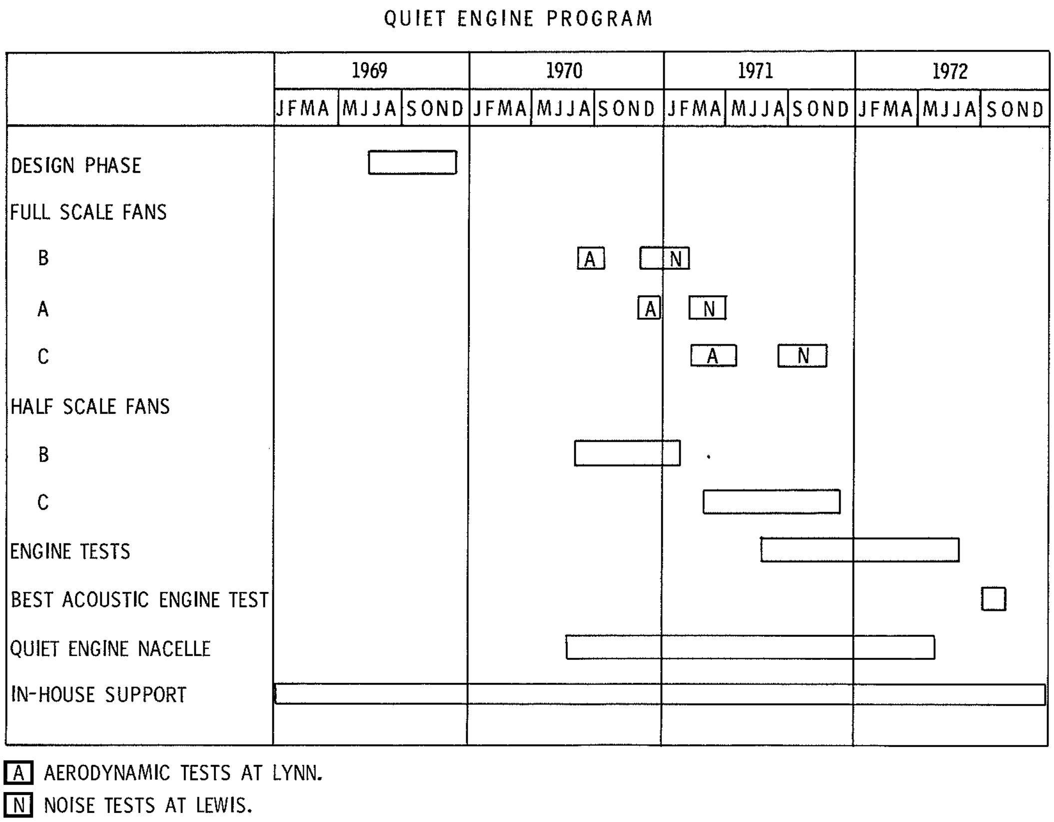

Figure 10. - Quiet engine program schedule.

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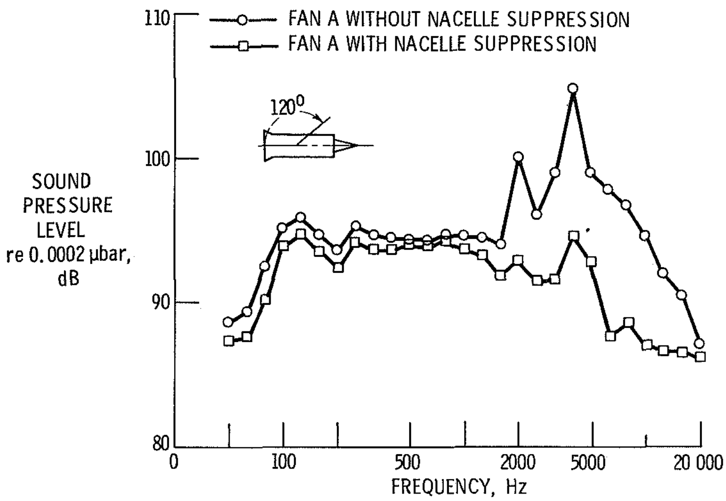
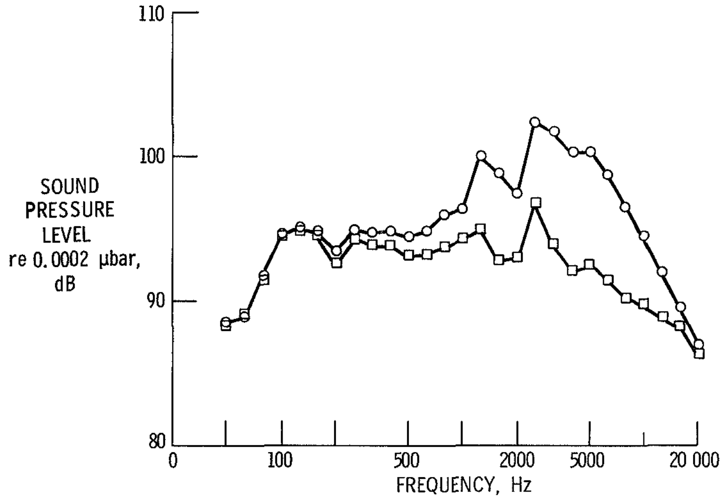


(A) FAN A.



(B) FAN B.

Figure 11. - One-third octave band noise spectra with and without suppression, 100 foot radius at 120°.